On anisotropy of magnetic fluctuations in the polar solar wind

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Abstract. We study the anisotropy of magnet ic fluctuations measured by the Ulysses s])acecraft in the fast solar wind from the south polar hole. The fluctuations in the range bet ween 1 min and half- an-hour are co1 isidered. These fluctuations are believed to be associated with a turbulent cascade of energy. We investigated several intervals when the spacecraft measurements sampled the solar wind along the mean magnetic field. These intervals are compared with others during which the spacecraft sampled the solar wind in the direction perpendicular to the mean magnetic field. We have also studied several examples of turbulence within CMEs observed try Ulysses at large latitudes. Although an anisotropy is detected, the anisotropy is found to be weak compared with the anisotropy of the solar wind fluctuations in the ecliptic plane or the anisotropy of the laboratory MHD plasma, The main cause of the difference is the large amplitude of fluctuations relative to the mean magnetic field. The results are discussed in relation to Ml 11) models of anisotropic turbulent.c.

Introduction

Solar wind fluctuations are considered to be composed of magnetohydrodynamic waves, mainly Alfvén waves [for a review see *Roberts* and *Goldstein*, 1991; and *Marsch*, 1991]. According to both theoretical and observational evidence, the interaction between these waves results in a turbulent cascade on small scales. In early studies, as a rule, the turbulence was treated as isotropic. The presence of a large-scale interplanetary magnetic field in the solar wind, however, distinguishes a direction, hence this turbulence is not expected to be isotropic. Indeed, *Matthaeus et al.* [1990] demonstrated, using ISEE-3 data, that the turbulence in the ecliptic plane near 1 AU is anisotropic. Recently *Matthaeus et al.*, [1994] and *Bieber et al.*, [1995] found that magnetic fluctuations observed by the Helios spacecraft in the ecliptic plane can be fit with a model in which the fluctuations consist of 85% two-dimensional wave turbulence developed in the plane perpendicular to the mean magnetic field, and 15% wave turbulence with the waves propagating along the mean field.

Anisotropic turbulence was first studied in laboratory plasmas. Plasma turbulence in pinches and tokamaks is highly anisotropic due to the imposed strong magnetic fields [see for example *Robinson and Rusbridge*, 1971]. The correlation length perpendicular to the magnetic field is much shorter than that parallel to the field.

In agreement with laboratory research and solar wind observations in the ecliptic plane, numerical simulations of MHD in the presence of an external d.c. magnetic field show the development of anisotropic turbulence from initially isotropic turbulence [*Shebalin et al.*, 1983; *Oughton et al.*, 1994]. Space studies are of special importance because high magnetic Reynolds number MHD turbulence cannot be produced in the laboratory, and it is difficult to simulate high magnetic Reynolds number MHD turbulence numerically.

Recently theoretical studies of MHD turbulence in an astrophysical context have been made by *Goldreich* and *Sridhar*, [1995]. These authors come to the conclusion that the well known theory of isotropic, MHD turbulence that predicts $k^{-3/2}$ spectrum [*Iroshnikov*, 1964; *Kraichnan*, 1965] is incorrect. A disagreement with some basic aspects of the Goldreich and Sridhar work has already been recorded [*Montgomery and Matthaeus*, 1994]. In the present paper (see also *Ruzmaikin et al*, [1995]) we show that isotropic MHD theory is a good approximation under conditions which are valid in the solar wind from the polar hole.

In this paper we study fluctuations in the solar wind from the south polar hole at high latitudes as measured by the Ulysses magnetometer. To look for the anisotropy we construct power spectra and correlation functions for periods when data were taken along the large-scale magnetic field and periods when data were taken in the direction perpendicular (or near perpendicular) to the field. We compare our observational results with MHD models predicting the form of spectra and the degree of anisotropy.

Ulysses data taken in high-speed wind from the polar hole (relatively undisturbed by CMEs and similar events) provide a unique tool for studying MHD turbulence. The high solar latitudinal position of the spacecraft allows the study of turbulence in regions of the solar wind different from those studied by other spacecraft. The Ulysses experiment [*Balogh et al.*, 1992; *Bame et al.*, 1992; *J. L. Phillips et al.*, 1995] is supplying us with excellent data on an important and fundamental physical problem.

Theoretical Background

Turbulence is commonly characterized by two spatial scales: a large scale at which the energy is input, and a small scale at which the energy is dissipated [*Monin and Yaglom*, 1975]. The interval between these scales, called the inertial range, is self-similar i.e. has no preferred scale. This self-similarity of the inertial range implies that the spectrum follows a power-law. The self-similar solutions exist at least in the limit of an ideal incompressible fluid described by the equations

$$\frac{\partial \mathbf{b}}{\partial t} + (\mathbf{v}\nabla)\mathbf{b} = (\mathbf{b}\nabla)\mathbf{v} \tag{1}$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\nabla)\mathbf{v} = (\mathbf{b}\nabla)\mathbf{b} - \nabla p \tag{2}$$

where v is the velocity field, **b** is the magnetic field normalized by the factor $(4\pi\rho)^{1/2}$, p is the density, and p is the pressure. These equations are invariant under the isotropic scaling transformations:

$$r \to \lambda r, \quad t \to \lambda^{1-h} t, \quad b \to \lambda^h b, \quad v \to \lambda^h v, \quad p \to \lambda^{2h} p, \tag{3}$$

where $\lambda > 0$ is an arbitrary constant. Transformations of the type presented in (3) have been discussed earlier for the hydrodynamic case [*Frisch*, 1983]. The exponent h can be defined by physical conditions. The condition commonly used, originally proposed for hydrodynamics by Kolmogorov, [1941] is that the rate of energy transfer be scale invariant, i.e.

$$\varepsilon \approx \frac{v_k^2}{\tau_K} \approx k v_k^3 \tag{4}$$

is independent of k. Here $\tau_K = 1/kv_k$ is the characteristic time for energy transfer. This condition immediately results in the Kolmogorov spectrum $h = 1/3$, or $k^{-5/3}$ for the one-dimensional spectrum

$$\int_k^{k+dk} E(k)dk \propto v_k^2. \tag{5}$$

When in addition to the random velocity field there is a uniform velocity, such as the solar wind velocity V_{SW}, the invariance (3) is still valid in the coordinate system co-moving with the wind. In contrast, the addition of a uniform magnetic field breaks the invariance [*Kraichnan*, 1965].

In the limit when the uniform magnetic field is weak compared with the fluctuating field (in the entire inertial interval or at least for small k), the invariant solutions (3) still exist, however the Kolmogorov exponent no longer pertains. This case is referred to as "strong turbulence". The turbulence now has the form of interacting random phased Alfvén waves propagating in the magnetic field b_0 associated with the largest scale k_0 of the cascade. In addition to the characteristic time τ_K, the decorrelation time of the waves $\tau_a = 1/kb_0$ must be considered. The characteristic time determining the rate of energy cascade can be estimated from the following physical considerations [*Kraichnan,* 1965; *Dobrowolny et al.,* 1980]. According to Eq. (1) the variation in amplitude of a given fluctuation b_k due to the nonlinear interaction is $\delta b_k \approx k b_k^2 \tau_a$. After N incoherent interactions the amplitude is $N^{1/2}\delta b_k$. Thus it takes $(1/kb_k)^2\tau_a^{-2} = (\tau_K/\tau_a)^2$ interactions to produce a variation comparable to the initial amplitude. The corresponding time for the nonlinear interaction is $\tau_n = (\tau/\tau_a)\tau_K$. Substituting this time, instead of τ_K, into (4) results in the spectrum $k^{-3/2}$ instead of the Kolmogorov spectrum.

Assuming that above reasoning is based on 3-wave resonant interactions *Goldreich and Sridhar,* [1995] claim that this interaction carries no energy; consequently the Kraichnan theory is incorrect. *Montgomery and Matthaeus,* [1995] have shown, however, that this claim is based on a semantic pitfall, and the triad interactions always carry an energy. It is worth noting also that *Kraichnan,* [1965] did not consider any specific type of interaction. Only dimensionless arguments have been used. We show in this paper, [see also *Ruzmaikin et al.,* 1995; Horbury et al., 1995], that in the regions of the solar wind where the magnetic field fluctuations are stronger than the mean field, the turbulence can be approximated as isotropic.

Note that in the solar wind, in addition to the energy, there is another integral, the so called cross-helicity $2\int \mathbf{v}\mathbf{b}d^3x$. Because of the Alfvén wave relation $\mathbf{v} = \pm\mathbf{b}$, the scale invariance of the cross-helicity reduces to the same condition as follows from the energy scale invariance. Thus no extra condition on h appears. However, a non-zero cross-helicity reduces the strength of the nonlinear interactions which are due to "collisions" of waves with the opposite sign of cross-helicity [*Kraichnan, 1965; Dobrowolny et al., 1980*].

In the other limiting case, when the mean magnetic field B is stronger than the fluctuating field ("weak turbulence"), scaling invariance can be recovered if one abandons the requirement of isotropy. Let v_k and b_k be the amplitude of the velocity and magnetic field perturbations respectively. These perturbations are perpendicular to **B** and are dependent on spatial scales parallel ($k_{\parallel}^{-1}$) and perpendicular ($k_{\perp}^{-1}$) to B. To check the invariant properties of Eqs. (1, 2) we replace them by order of magnitude expressions. For example, instead of Eq. (1) we use

$$\frac{\delta b_k}{\tau_A} \propto Bk_{||}v_k + b_k k_{\perp} v_k \tag{6}$$

where $\tau_A \propto 1/k_{||}B$ is now the smallest characteristic time. The invariance (3) is generalized as

$$k_{\perp} \to \lambda^{-1} k_{\perp}, \quad t \to \lambda^{1-h} t, \quad b_k \to \lambda^{-h} b_k, \quad v_k \to \lambda^{-h} v_k, \quad p_k \to \lambda^{-2h} p_k, \quad k_{||} \to \lambda^{h-1} k_{||} \tag{7}$$

The immediate consequence of this invariance is some degree of anisotropy. The spectrum of fluctuations has the form

$$k_{||} \propto \quad k_{\perp}^{1-h}, \tag{8}$$

$$b_k \propto \quad k_{\perp}^{-h} \tag{9}$$

Only scaling manipulations have been used to this point. No physics has been involved. Let us turn to physics to determine the exponent h.

The first term on the right hand side of Eq. (6) describes the propagation]] of Alfvén waves along the large-scale magnetic field. The second term refers to the nonlinear interactions between the waves which drive the turbulent cascade. From the physical point of view, the interaction is carried out by "collisions" of oppositely directed Alfvén waves [*Kraichnan*, 1965]. In order to have a consistent picture of the Alfvén wave cascade, these two terms are expected to be equally important, i.e.

$$Bk_{||} \approx k_{\perp} v_k \tag{10}$$

Put differently, if this condition is valid it implies the approximate equality of the three characteristic times $\tau_\perp = 1/k_\perp v_k$, τ_A and $\tau_\perp^2/\tau_A$. The third time defines the rate of nonlinear transformation of energy from scale k to scale $2k$. Also due to this condition $(\delta b_k)^2$ is of the same order as b_k^2. The rate of energy transfer in the cascade takes the very simple form

$$\varepsilon \approx \frac{(b_k)^2}{\tau_A} \approx k_{\|} B b_k^2 \propto k_\perp^{1-3h} \tag{11}$$

This gives $h = 1/3$. The anisotropization of MHD turbulence by this type of mechanism was studied numerically by *Shebalin et al.*, [1983]. The anisotropic spectrum $h = 1/3$ is discussed in an astrophysical context by *Goldreich and Sridhar*, [1995].

To establish a correspondence between the theory and observations we have to take into account that spacecraft data are obtained as a time series at a given spatial point. however, they reflect the spatial distribution of the fields in so far as fluctuations earl be considered as being frozen into the supersonic solar wind; that is, the Taylor hypothesis holds [*Matthaeus and Goldstein*, 1982]. In practice, instead of the Fourier amplitudes, the one-dimensional spectrum (5) is always used. In the anisotropic situation we can define the one-dimensional spectrum as follows: (a) for measurements taken in a direction perpendicular B

$$E_\perp \propto \frac{b_k^2}{k_\perp} \propto k_\perp^{-2h-1} \tag{12}$$

(b for measurements taken in a direction along B

$$E_{\|} \propto \frac{b_k^2}{k_{\|}} \propto k_\perp^{-(1+h)} \propto k_{\|}^{-\frac{1+h}{1-h}} \tag{13}$$

With $h = 1/3$ one has $E_\perp \propto k_\perp^{-5/3}$ and $E_{\|} \propto k_\perp^{-4/3} \propto k_{\|}^{-2}$. This "weak turbulence" result is different from the "strong turbulence" result discussed above.

in this discussion we have not used the terminology of the specific models such as the 2-D and slab models which assume that waves propagate only along or only across the mean magnetic field (for details see review *Matthaeus et al.* [1994] with references therein). We have just referred to a simple isotropic approximation and an extreme anisotropic case. Some of the measures of anisotropy calculated below can, however, be used for testing these models.

It is worth while to discuss the problem of the kind of measure that can be used for the specification of anisotropy in observational studies. Observationally, we have a time series of the three components of the magnetic field. The idea, first used by *Sari and Valley*, [1976] in their study of the Pioneer 6 data, is to construct power spectra, and correlation functions for periods when the data were taken along the large-scale magnetic field and for periods when the data were taken in the direction perpendicular to the large-scale magnetic field. (Data always are taken along the heliospheric radial direction because the solar wind velocity is essentially radial.) More generally, the statistical properties of fluctuations are expected to be dependent on the angle between the mean field and direction in which the spacecraft takes the data.. This more general approach was used by *Matthaeus et al.* [1990] in their study of 15 min-averages of ISEE 3 magnetic field data.

In this paper we restrict ourselves mainly to the study of periods when the mean magnetic field was nearly parallel and nearly-perpendicular to the direction of data acquisition. Because the spacecraft measures the magnetic field in the radial flow of the solar wind, the existence of such intervals depends on the angle between the radial direction and mean magnetic field. Figure 1 shows this angle for a time period starting from July 1993 when the spacecraft was at about 4.4 AU from the Sun and at -37.8° heliolatitude and ending in December 1994 when the spacecraft was at 1.57 AU and -44.8° heliolatitude. There is a global trend towards a radial field as the spacecraft goes towards the pole, in general accordance with the evolution of the Parker spiral field. One can also see that the angle fluctuates relative to the trend corresponding to the Parker field, so that periods when the daily averaged magnetic field is nearly perpendicular or nearly parallel to the radial direction are available.

We first select periods with no CMEs, shocks, and other disturbances. Separately, we then investigate the turbulence inside several CMEs. The mean magnetic field is defined for each time series as the average over the whole interval considered. Then we transform the original data into a coordinate system in which the x component is along the mean field, y component is perpendicular to the plane defined by the mean field and the radial direction i.e. the direction of the velocity of the solar wind, and z completes the orthogonal system.

We use the following quantities to characterize the anisotropy:

(1) The ratio of power along the large-scale magnetic field to the total power in the perpendicular directions:

$$P_a = \frac{\sum(S_{yy} + S_{zz})}{2\sum S_{xx}}$$

(2) The ratio of power in the direction perpendicular to the plane defined by the mean magnetic field and the radial direction to the power in the other direction perpendicular to the mean field:

$$\delta = \frac{P_{yy}}{P_{zz}} = \frac{\sum S_{yy}}{\sum S_{zz}}$$

It is expected [*Bieber et al., 1995*] that in the slab model (when waves propagate only along the mean field) this ratio is equal to one, and in the 2-D (when waves propagate almost perpendicular to the mean field) the ratio is larger than one and that the ratio is an increasing function of the angle between the mean field and the radial direction.

(3) The correlation time for the field component along the hwgc-scale magnetic field and correlation times for the components perpendicular to the large-scale magnetic field. The correlation time τ is defined as the point at which the (auto) correlation function for the corresponding component drops by a factor of two. The correlation length can be inferred from the correlation time by multiplying by the solar wind velocity.

It is expected [markcite*Bieber et al.,* 1995] that in the slab model τ_x is the shortest correlation time, and in the 2-D τ_x is the longest correlation time.

(4) the spectral exponents for measurements made "along" the large-scale magnetic field and in the "perpendicular" directions.

Anisotropy of Magnetic Field Fluctuations in Undisturbed Regions

We analyze several 1-min-averaged time series for the magnetic field. These time series are taken from the data obtained by Ulysses in the fast solar wind from the south polar hole. The spectra for these time series are calculated with the help of the structure functions

$$S_{ii}(\tau) = \langle (b_i(t+\tau) - b_i(t))^2 \rangle$$

where $i = x, y, z$; τ is a variable time-lag, and the averaging is taken over all t of the data set [*Ruzmaikin et al.,* 1995; *Horbury et al.,* 1995]. Note that $S(0) = 0$ and $S(\infty) = 2\langle |b_i|^2 \rangle$ [*Monin and Yaglom,* 1975]. For correlation analysis we use the (auto)correlation functions $C(\tau) = \langle b_i(t+\tau) b_i(t) \rangle$ which are simply related to the structure function: $S(\tau) = 2(\langle b_i^2 \rangle - C(\tau))$. In the inertial interval the structure functions scale as $S_{ii}(\tau) \propto \tau^{s_i(2)}$ where the exponent is directly related to the spectral exponents α_i of each component, $\alpha_i = 1 + s_i(2)$.

For a Gaussian distribution of turbulent fields, the knowledge of these (second-order) structure functions is sufficient to characterize the turbulence [*Monin and Yaglom,* 1975]. However, the observed fields are intermittent, i.e. non-Gaussian [see *Feynman and Ruzmaikin,* 1994 and references in that paper] so that the structure functions of higher order are needed. In general, the p order structure functions scale as $\tau^{s(p)}$, i.e every structure function has its own exponent. These exponents allow a "correction" to the second-order spectral exponent to be found [*Ruzmaikin et al.,* 1995]. We do not make these corrections in this paper. Note only that in the case of a normal turbulent cascade (the energy cascades from large scales to sm al 1 scales) the corrections arc always negative, i.e. the observed spectral exponents will be higher than those predicted from the scco]ld-order theories.

The Ulysses spacecraft was well within the solar wind from the south polar hole in late 1993. The solar wind speed was consistently in the 700" to 800 km/s range. Compressions, rarefactions an d shock waves had weakened or d isappeared. There were few coronal mass ejections [*Phillips et al.,* 1995]. in bi icf, we had a steady fast solar wind with few large-scale disturbances. These data present a unique opportunity to study the waves and turbulence in an undisturbed wind. In our previous study [*Ruzmaikin et al.,* 1995; *],* see also [*Horbury et al.,*]995] , we found that the spectrum is self-similar on time scales between 1 min and about half an hour. The corrected spectral index in this region has been estimated to be consistent with 3/2. *Horbury et al., [1* 995] have shown that the spectrum at lower frequencies has a spectral exponent about $\alpha = 1$, and it is unaffected by intermittency. The present study focuses on frequency range corresponding to the time range between 1 min. and 16 min in which spectra have a clear power-law form (In some cases this interval can be extended to half an hour or more). Wc use several 1- rein- averaged data sets from the Ulysses magnetometer [*Balogh et al.,* 1992]. The duration of time series used is between about one and three days. (There arc 1440 data points in a day.) Only those time series are selected for which the angle between the radial direction and mean magnetic field, determined from the curve in Figure 1, remains essentially unchanged.

We select for our analysis several undisturbed t ime periods when the spacecraft was at large heliocentric latitudes. The first time interval covers days 258 and 259, 1993, when the angle between the radial direction and mean magnetic field was close to 90° (see l'able 1). In two other intervals, days 273- 274 (III in '1'able 1), and days 318-320 (IV in ~'able 1), 1994, the mean field was almost antiparallel to the radial direction.

The results for an interval (II) with an intermediate angle are presented in Table 1. The ratio of particle pressure to magnetic pressure (the plasma parameter β) is greater than one for all time series considered [*J.* L. *Phillips et al., 1995].*

Figure 2 shows the deviations of the magnetic field components from the mean field for the first data set i.e. for the 258-259, 1994 interval when data are taken in the direction perpendicular to the mean magnetic field itself, Note that the variations of the components of the magnetic field are larger than the mean field. There is no anisotropy in the power measured by δ indicating that the slab model is a good approximation to this data set.

The magnetic field data in Figure 2 are used to calculate the autocorrelation functions for each component (Figure 3). The correlations in all three components decrease quite smoothly with lag τ with a correlation time in the direction of the mean field being intermediate between the correlation times for the other components. Figure 4 shows the second-order structure functions for this data set in the self-similar range. In the calculation of the structure functions we use $\tau = 2^{j/2}$, j = 0,1,2, . . . in the units 1 min as the time lag. The spectral exponents for the three components are almost equal; at least we could not distinguish them within our accuracy +0.1.

The results of calculations are presented in Table 1 for all data sets used. In the 'Table 1 α is the observed slope of the power spectrum found with a help of the second-order structure function. Within the accuracy of our calculation we could not say that the spectra] exponents are systematically different in different directions or for different angles ψ. The ratio of the power perpendicular to the mean field to that along the mean field is always larger than one (Table 1) in accordance with the Alfvén wave character of the turbulence. The ratio of the powers in two perpendicular directions is variable but does not show any systematic angular dependence. If the turbulence is highly anisotropic the correlation time in the x-direction would be much larger than in the other directions. This is not the case for any of the time series. Note that for all intervals studied the ratio of the fluctuating field to the mean field $\delta B/B$ is large (see the last column in Table 1). This ratio is defined as the ratio of the sum of standard deviations for the three field components to the mean field,

Thus we tend to conclude that the strong turbulence observed in the undisturbed solar wind from the polar hole can be described by an isotropic approximation. Unless there is a model capable of characterizing the amount of observed anisotropy.

Anisotropy of Fluctuations within CM Es

The turbulence in the undisturbed polar wind is strong ($\delta B/B > 1$). However $\delta B/B$ is smaller in regions within coronal mass ejections observed in the solar wind. Although the fluctuations within CMEs may nave a different nature from these in the undisturbed wind it is nevertheless interesting to investigate the anisotropy of these relatively weak fluctuations. J. Gosling has identified CMEs in the Ulysses data (private communication), and we have chosen three: of these CMEs in which the ratio $\delta B/B$ is less than one and the magnetic field fluctuations appear to be turbulent. Figures 6-8 show the data, st ructure functions and correlation functions for a CME observed on days 111-112, 1994. The results for this and two other CMEs are compiled in 'J'able 2.

Although the fluctuations of the field are still large, they are smaller than the mean field magnitude. The correlation function in the first case in Table 2 is strongly influenced by structures within the CME for time lags larger than about 20 min. Therefore meaningful correlation times in this case could not be determined. However from the behavior of the correlation function for τ's si nailer than 20 min we find that $\tau_z < \tau_y < \tau_x$. In this sense the first case in Table 2 is consistent with the predictions of the anisotropic 2- 1) model. In the other two cases the ratios of the correlation times are not in accordance with the 2-D model, Although no conclusions can be derived from these small number of cases, the weak MHD turbulence within CMEs appears to have the same spectra] exponent as the strong turbulence in the polar wind. '1'here is some evidence for increased anisotropy in the power ratios P_a and δ.

Discussion

Our results, while not obtained by extended statistically study, evidence that the turbulence from the polar holes is less anisotropic than the turbulence in the ecliptic plane. It is interesting that before the launch of the Ulysses *Roberts,* [1 980] using evolutionary arguments predicted that the polar fluctuations were likely to be nearly isotropic.

We do not find any essential differences in the spectral slopes for the power calculated in different directions. We believe that the basic cause of the near isotropy is the large magnitude of the fluctuating field compared with the mean field (the strong turbulence), and, perhaps, the large plasma β. In fact, the study of the turbulence inside CMEs where the fluctuating magnetic field is relatively small (turbulence is weaker) suggest an increase of the degree of anisotropy as measured by the power ratios P_a arid δ.

Our results do not confirm the anisotropy of the spectrum which would have been expected from the theoretical considerations by *Goldreich and Sridhar, [1 995]*. The basic inconsistency is perhaps not 5/3 for the time series taken perpendicular to the mean field but absence of a tendency towards the $k_{\|}^{-2}$ spectrum for the time series taken in directions away from the perpendicular (time series 111 and IV in the Table 2). [Note also that an intermittency correction to the observed spectrum implies that the spectral exponent is even less than that presented in Tables 1 and 2.]. Even in the weak turbulence case our results arc somewhat consistent with isotropic approximation to the MHD turbulence.

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References

Balogh, A., T. J. Beek, R. J. Forsyth, P. C. Hedgecock, R. J. Marquedant, and E. J. Smith, The magnetic field investigation on the Ulysses mission: Instrumentation and preliminary results, *Astron. Astrophys., Suppl.* Ser., 92, 2.21, 1992.

Balogh, A., G. Erdos, R. J. Forsyth, and E. J. Smith, The evolution of the interplanetary sector structure in 1992, *Geophys. Res. Lett.*, 20, 2331, 1993.

Bame, S. J., D. J. McComas, B. L. Barraclough, J. L. Phillips, K. J. Sofaly, J. C. Chavez, B. E. Goldstein, and R. K. Sakurai, The Ulysses solar wind plasma experiment, *Astron. Astrophys., Suppl. Ser.*, 92, 237, 1992.

Bieber, J, W., W. Wanner, and W. H , Matthaeus, Dominant two- dimensional solar wind turbulence with implications for cosmic ray transport, submitted to *J. Geophys. Res.*, 1995.

Dobrowolny, M., A. Mangeney, and P. Veltri, Fully developed anisotropic hydromagnetic turbulence in interplanetary space, *Phys.* Rev. *Lett., 45*, 144-147, 1980.

Feynman, J., and A. Ruzmaikin, Distributions of the interplanetary magnetic field revisited, *J. Geophys. Res., 99*, 17, 645, 1 994.

Phillips, J. L., S. J. Bame, W. C. Feldman, B. E. Goldstein, J. T. Gosling, C. M. Hammond, D. J. McComas, M. Neugebauer, E. E. Scime, and S. T. Suess, *Science, 268*, 1030, 1995.

Frisch, U., in *Turbulence and Predictability of Geophysical Flows and Climate Dynamics,* Varenna Summer School LXXXVIII, 1983.

Horbury, T. S., A. Balogh, R. J. Forsyth, and E. J. Smith, Magnetic field signatures of unevolved turbulence in polar flows, *J. Geophys. Res.*, 1995 (submitted).

Iroshnikov, P. S., Turbulence of a conducting fluid in a strong magnetic field, *Soviet Astron. J., 7*, 566, 1964 [translated from *Astron. J., 40,* 742, 1963].

Kolmogorov, A. N., The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers, Dokl. Akad. Nauk SSSR, *30,* 301, 1941.

Kraichnan, R., Inertial-range spectrum of hydromagnetic turbulence, *Phys. Fluids, 8,* 1385, 1965.

Matthaeus, W. H., and M. L. Goldstein, Measurements of the rugged invariants of magnetohydrodynamic turbulence in the solar wind, *J. Geophys. Res.,* 6'7, 6011, 1982.

Matthaeus, W. 11., M. I,. Goldstein, and D. A. Roberts, Evidence for the presence of quasi-two-dimensional nearly incompressible fluctuations in the solar wind, *J. Geophys. Res.*, *95*, 20,673, 1990.

Matthaeus, W. 11,, J. W. Bieber, and G. P. Zank, Unquiet on any front: anisotropic turbulence in the solar wind, in *IUGG Quadrennial Report: 1991-1994, SPA Section* ed. by G. Siscoe, 1995.

Montgomery, D., and W. H. Matthaeus, Anisotropic modal energy transfer in interstellar turbulence, Preprint , Bartol Research Institute, submitted to *Astrophys. J., 1995.*

Monin, A. S., and A. M. Yaglom, *Statistical Fluid Mechanics: Mechanics of Turbulence, vol. 2,* MIT Press, Cambridge, Mass., 1975.

Oughton, S., E. R. Priest, and W. H. Matthaeus, The influence of a mean magnetic field on three-dimensional magnetohydrodynamic turbulence, *J. Fluid Mech., 280* 95, 1994.

Roberts, D. A., Turbulent polar heliospheric fields, *Geophys. Res. Lett.*, 17, 567, 1990.

Roberts, 1). A., and M. L. Goldstein, Turbulence and waves in the solar wind, Suppl. to *Rev. Geophys., 29, 1991.*

Robinson, 1). C., and M. G. Rusbridge, Structure of turbulence in the Zeta plasma, *Phys. Fluids, 14, 2499,* 1971.

Ruzmaikin, A. A., J. Feynman, B. E. Goldstein, E. J. Smith, and A. Balogh, Intermittent turbulence in the solar wind from the south polar hole, *J. Geophys. Res., 100,* 3395-3404 , 1995.

Sari, J. W., and G. C. Valley, Interplanetary magnetic field power spectra: Mean field radial or perpendicular to radial, *J. Geophys. Res., 81*, 5489, 1976.

Shebalin, J. V., W. H. Matthaeus, and 1). Montgomery, Anisotropy in MHD turbulence due to a mean magnetic field, *J. Plasma Phys.,* 29, 525, 1983.

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Figure Captions

Figire 1. The angle between the radial direction and hourly-averaged magnetic field for the period starting day 240, 1993 and ending day 365, 1994.

Figire 2. The magnetic field during the period 258259, 1994. The x-coordinate is along the mean field. The mean field and long-term linear trend are removed from the data.

Figire 3. Correlation functions for the magnetic field components for the time series taken on days 258-259, 1993.

Figire 4. Structure functions for the magnetic field components and the invariant trace of the field obtained from the time series taken on days 258-259, 1994. The fluctuations are self-similar in this time range. The slope gives the spectra] exponent.

Figire 5. Correlation functions for the magnetic field components for the time series taken in the days 318-320, 1994 (interval IV in '1'able 1), The mean magnetic field in this period is almost antiparallel to the radial direction.

Figire 6. The magnetic field in a CME observed during the period 111-112, 1994. The mean field is removed from the data for the components.

Figire 7. Correlation functions for the magnetic field in the CME for the time series taken in the days 111-112, 1994.

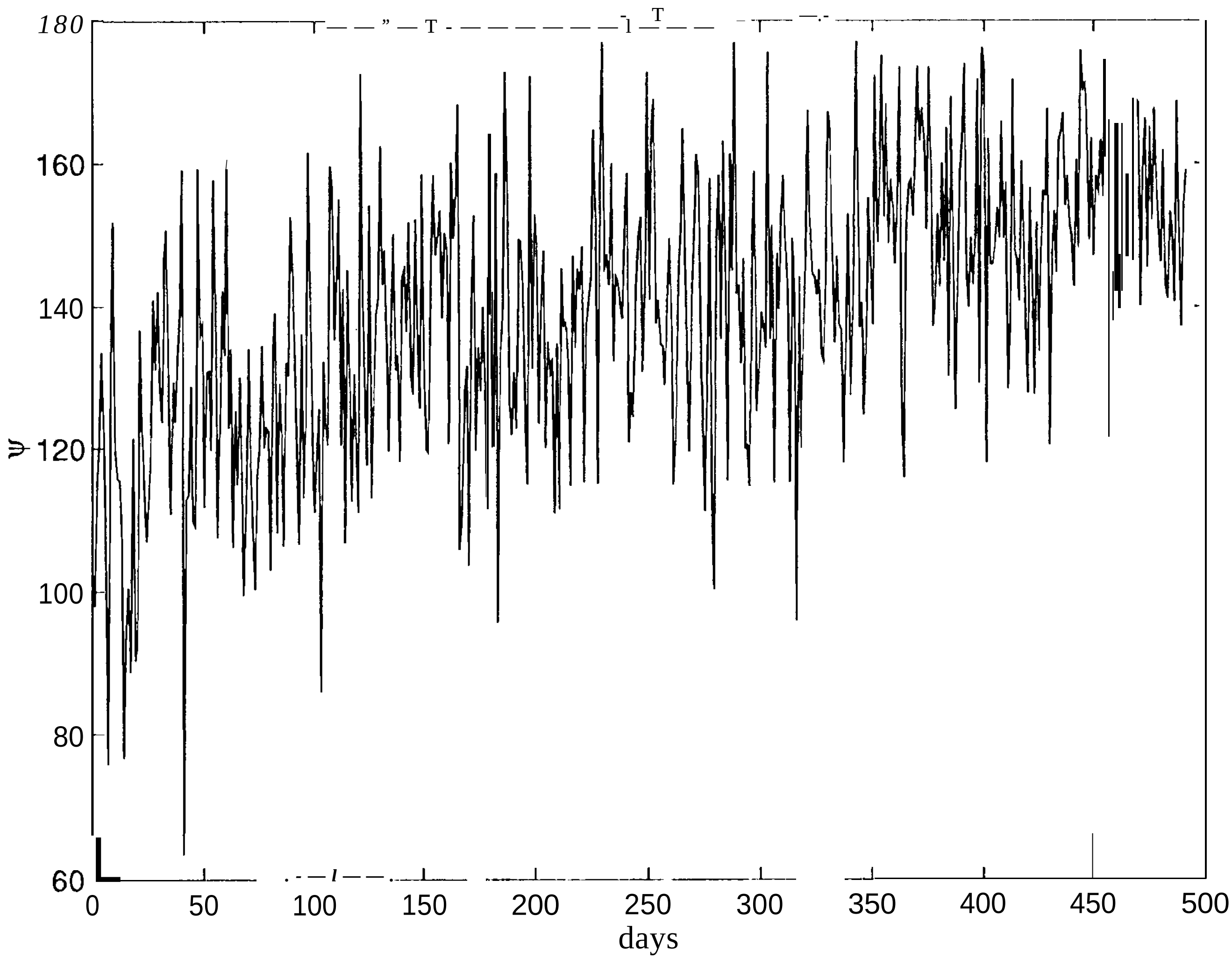
Figire 8. Structure functions for the magnetic field components and the invariant trace of the. field in the CME (from the time series taken in the days 111-112, 1994).

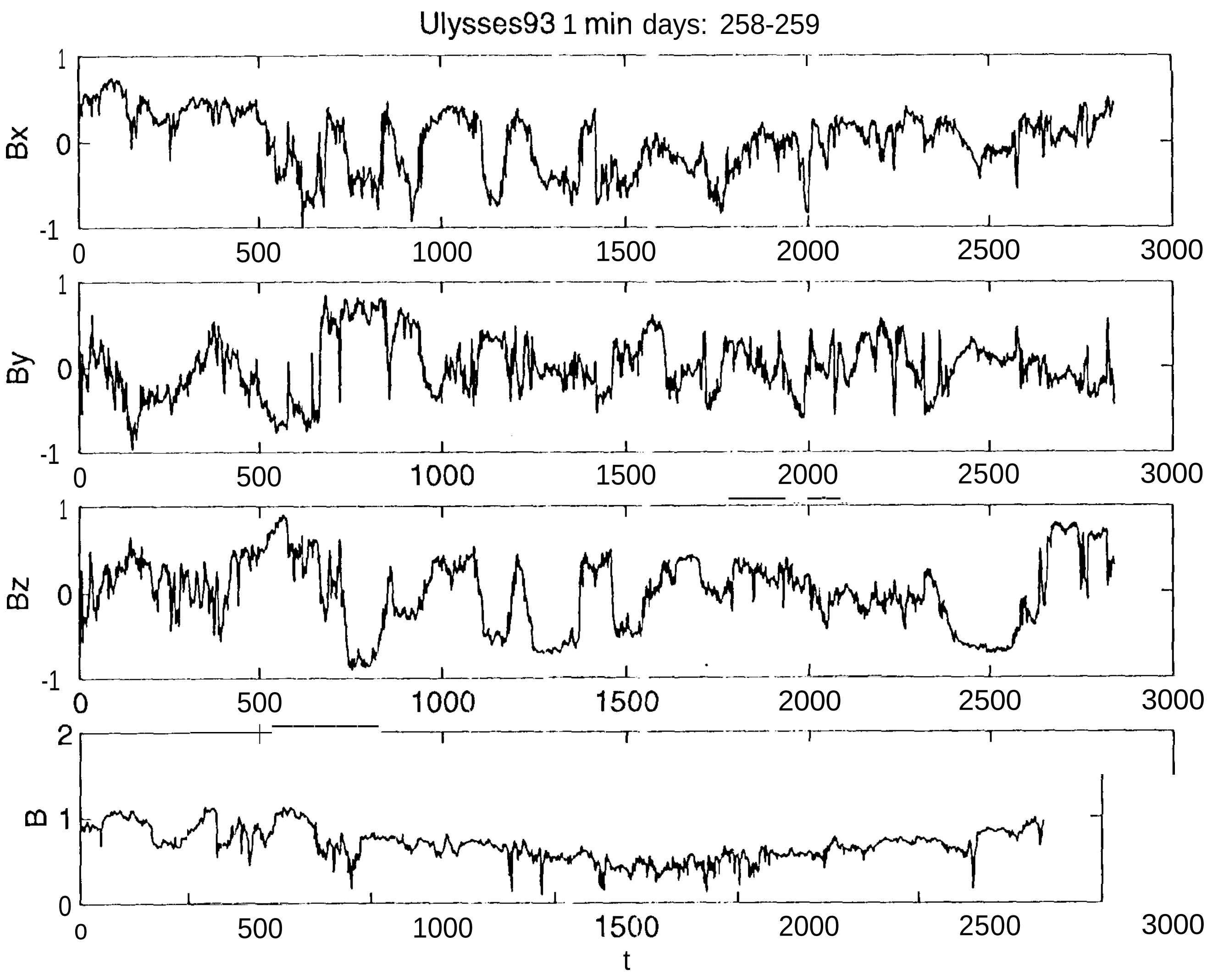
Table 1. The Angle Between the Radial Direction and Mean Field ψ, the Power Anisotropy P_a, the Ratio δ of Powers in Two Perpendicular Directions, Correlation Times $\tau_{x,y,z}$ and Spectral Indices α for the Magnetic Fields Components. The interval I corresponds to days 258-259, 1993, II stands for day 275, 1994, III stands for days 273-274, 1994, and IV stands for three days interval 318--320, 1994

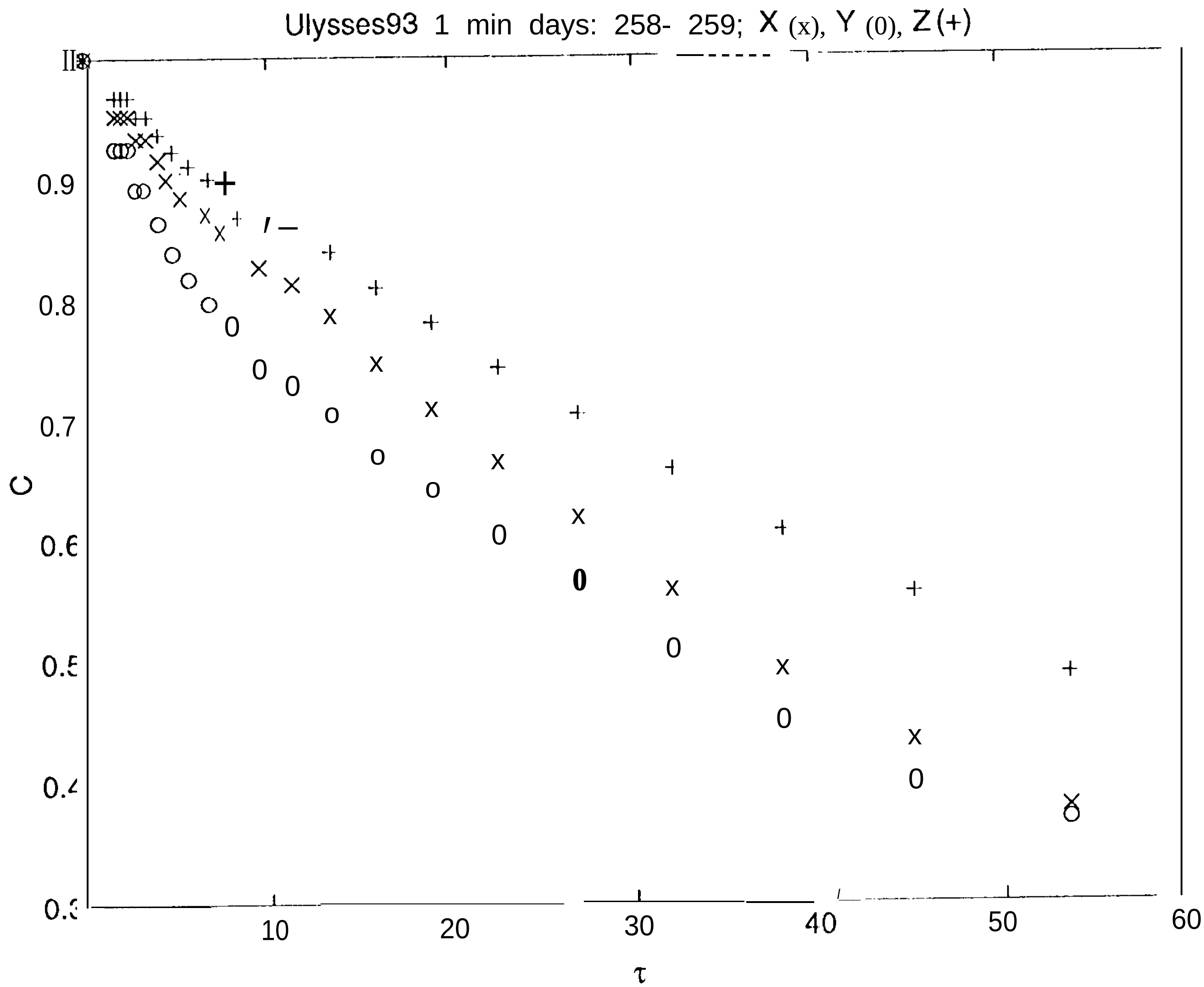
	ψ	P_a	δ	τ_x	τ_y	τ_z	α_x	α_y	α_z	$\delta B/B$
I	91°	1.1	1.0	38	38	54	1.7	1.6	1.8	2
II	118°	1.4	1.6	19	10	16	1.7	1.6	1.6	2.5
III	175°	1.6	1.2	10	23	16	1.6	1.7	1.6	1.5
IV	173°	1.8	1.2	10	13	32	1.6	1.6	1.6	1.4

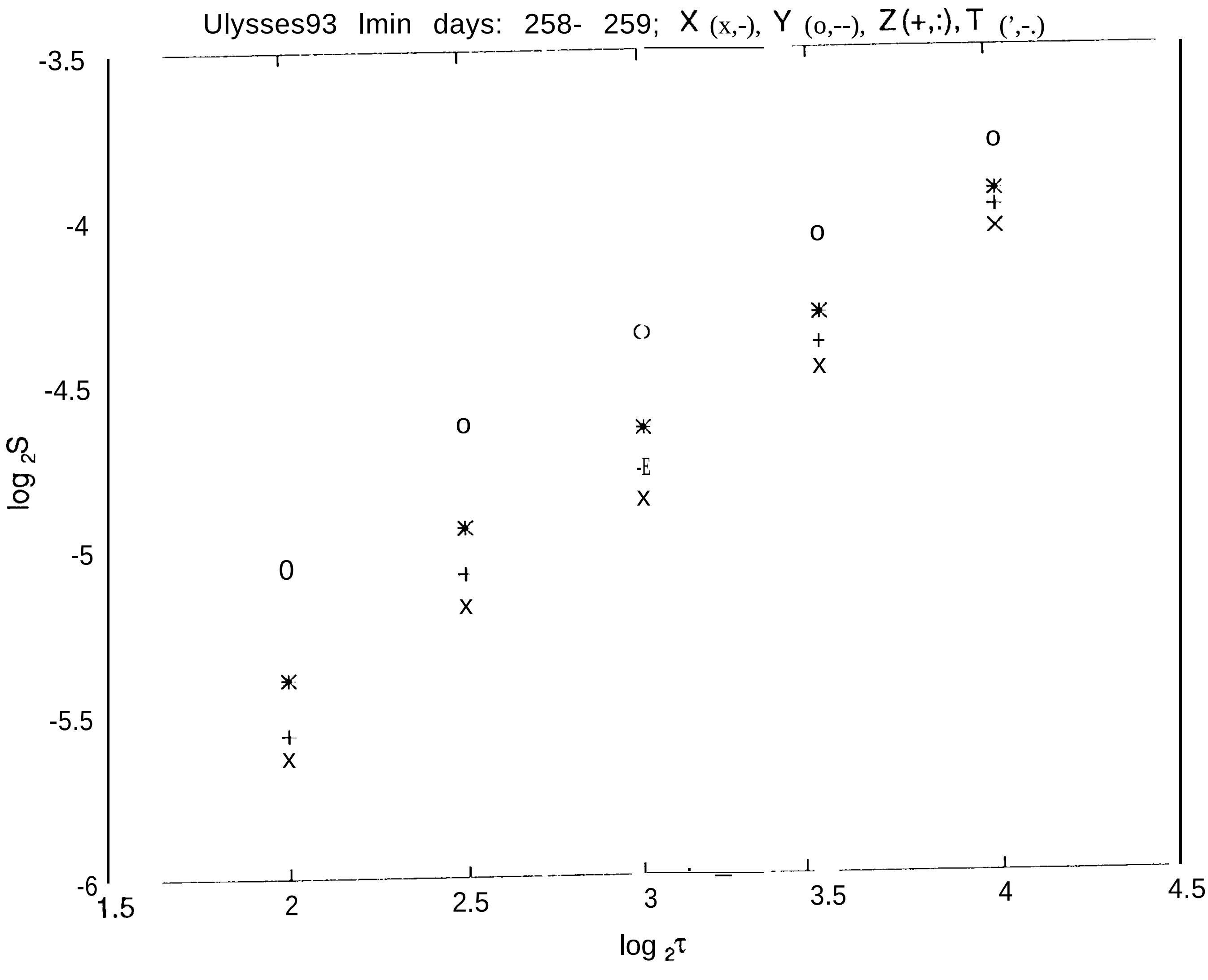
Table 2. The Angle Between the Radial Direction and Mean Field ψ, the Power Anisotropy P_a, the Ratio δ of Powers in Two Perpendicular Directions, Correlation Times $\tau_{x,y,z}$ and Spectral Indices α for the Magnetic Fields Components inside Chills. 'he interval 1 stands for days 40-41, 1994, II corresponds to days 58--59, 1994, and 111 stands for two days interval 111--112, 1994

	ψ	P_a	δ	τ_x	τ_y	τ_z	α_x	α_y	α_z	$\delta B/B$
1	93°	1.7	.8	-	-	-	1.7	1.5	1.7	0.5
II	134°	2.6	.2	10	19	38	1.5	1.7	1. 7	0.85
111	134°	4	.7	7	16	10	1.5	1.7	1.6	0.7

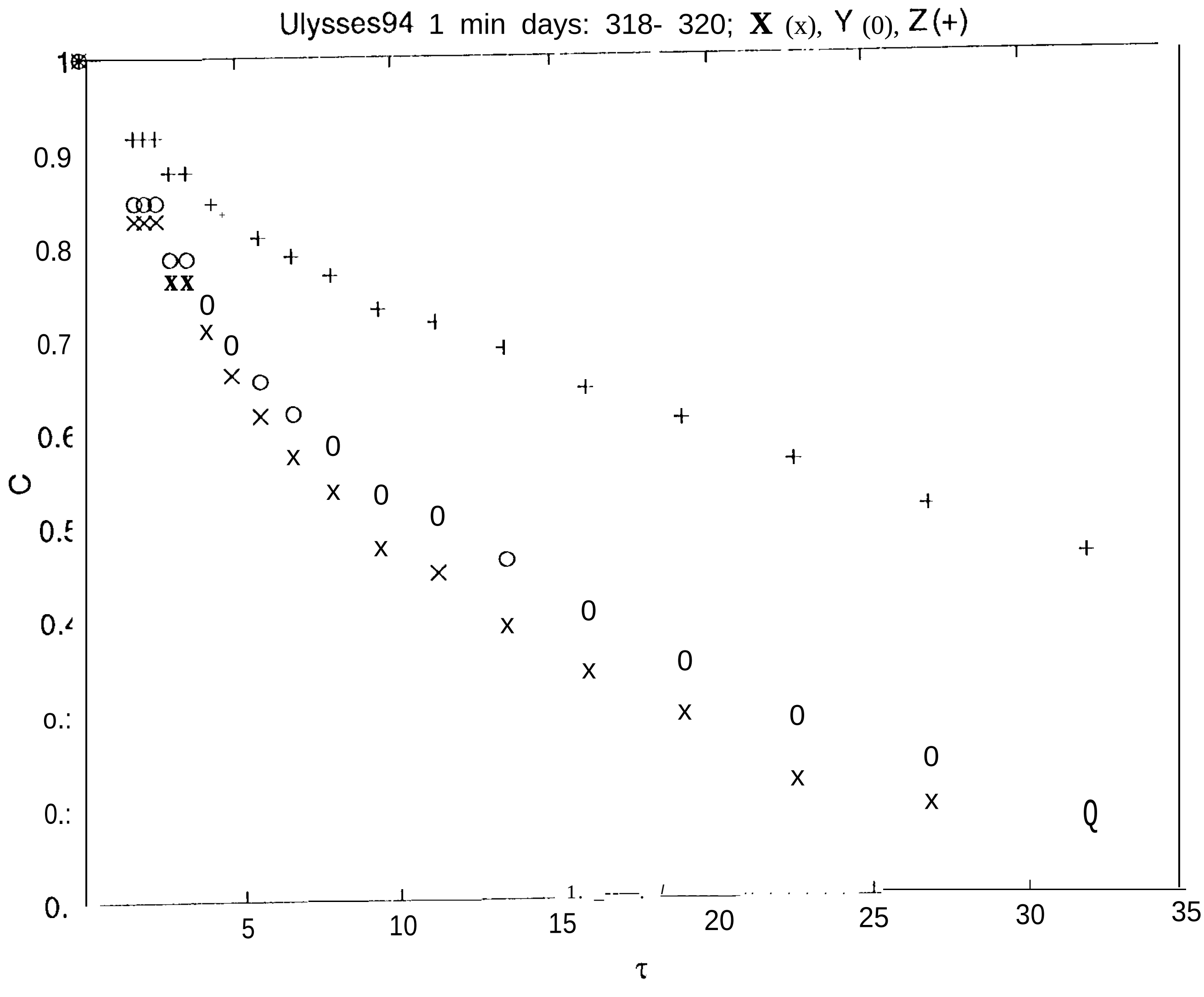

180
160
140
120
100
80
60
ψ
0
50
100
150
200
250
300
350
400
450
500
days


Ulysses93 1 min days: 258-259
Bx
By
Bz
B
t
0
500
1000
1500
2000
2500
3000

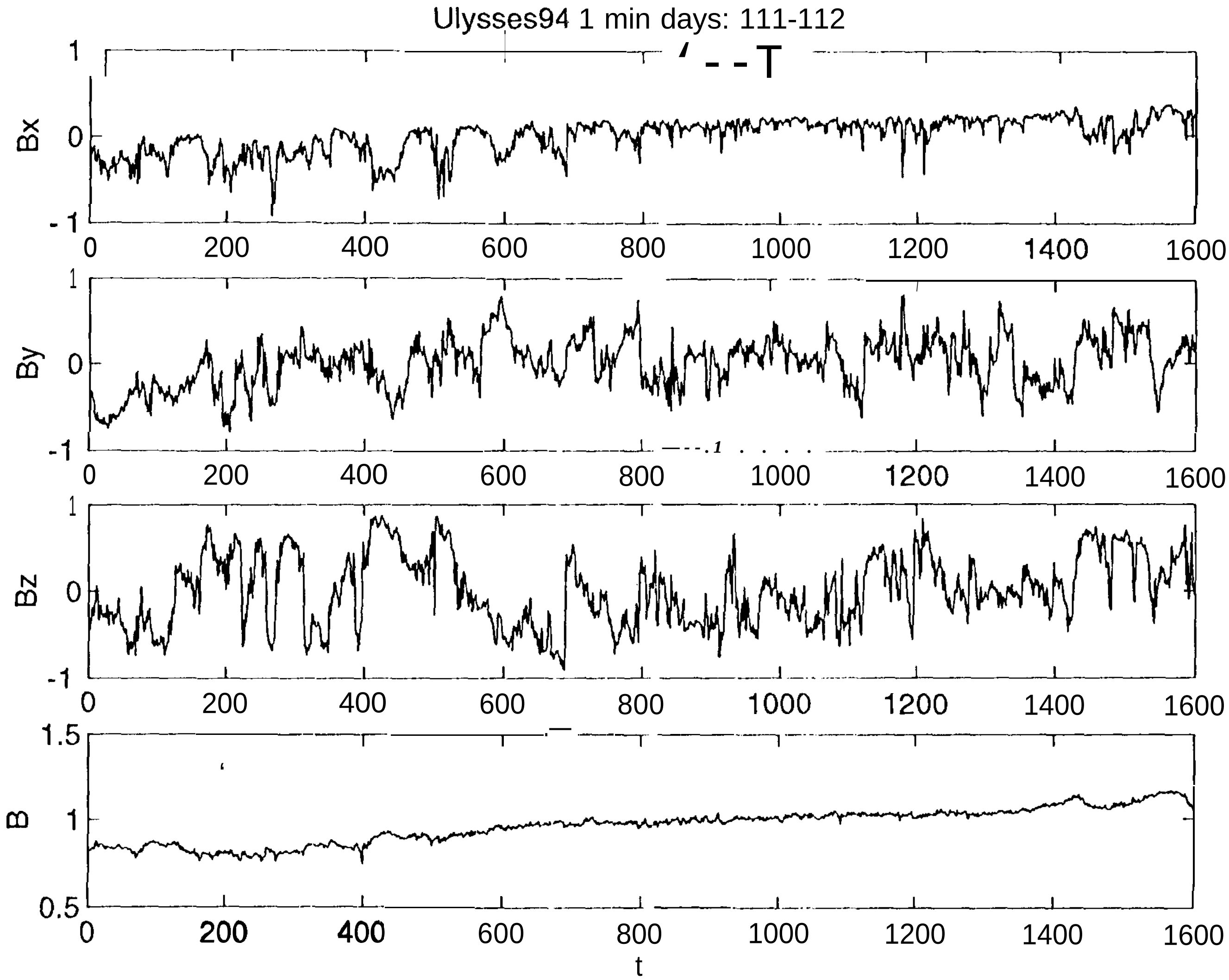

Ulysses93 1 min days: 258- 259; X (x), Y (0), Z (+)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
C
10
20
30
40
50
60
τ



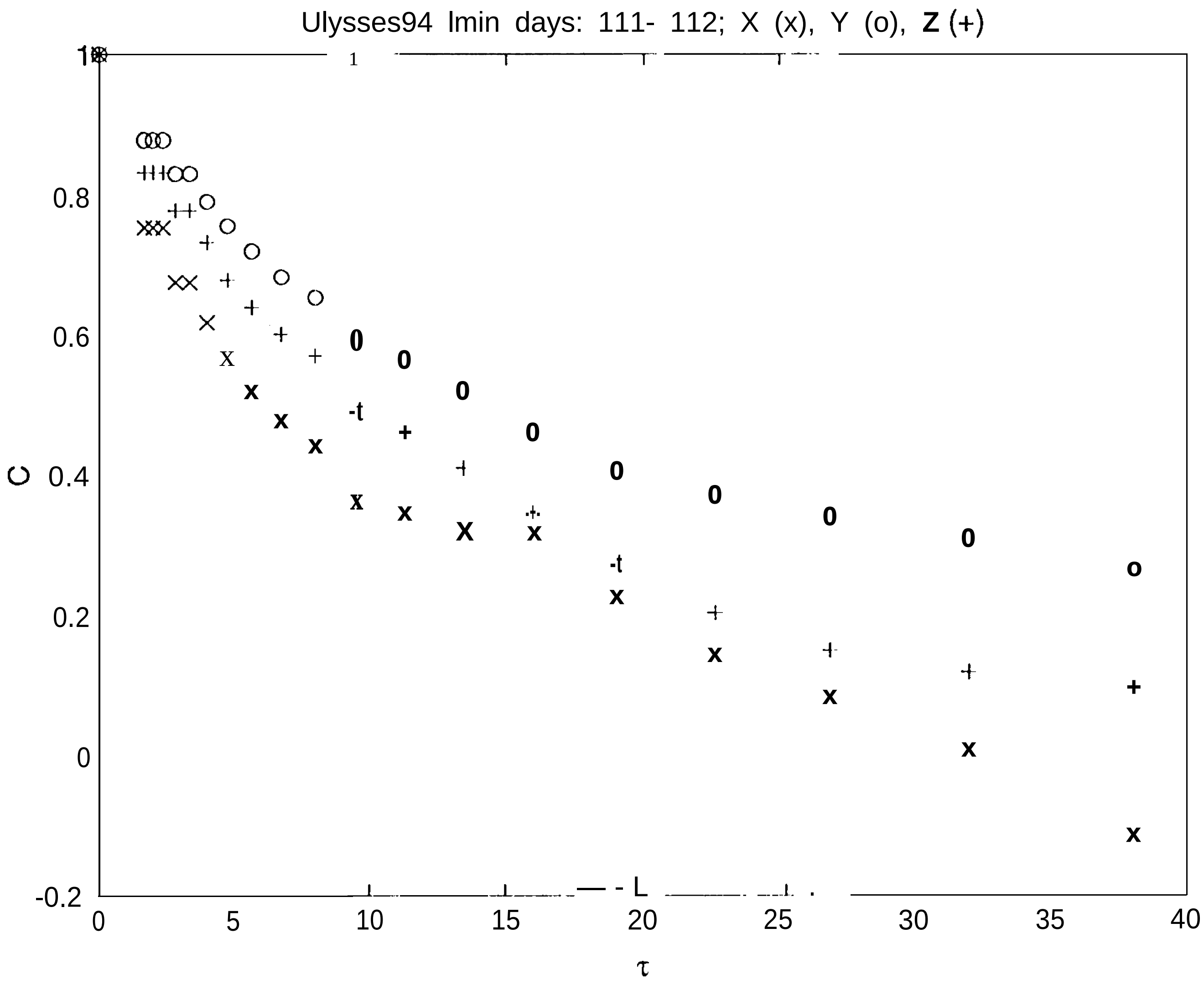
Ulysses93 lmin days: 258- 259; X (x,-), Y (o,--), Z(+,:), T (',-.)
-3.5
-4
-4.5
-5
-5.5
-6
log 2S
1.5
2
2.5
3
3.5
4
4.5
log 2τ

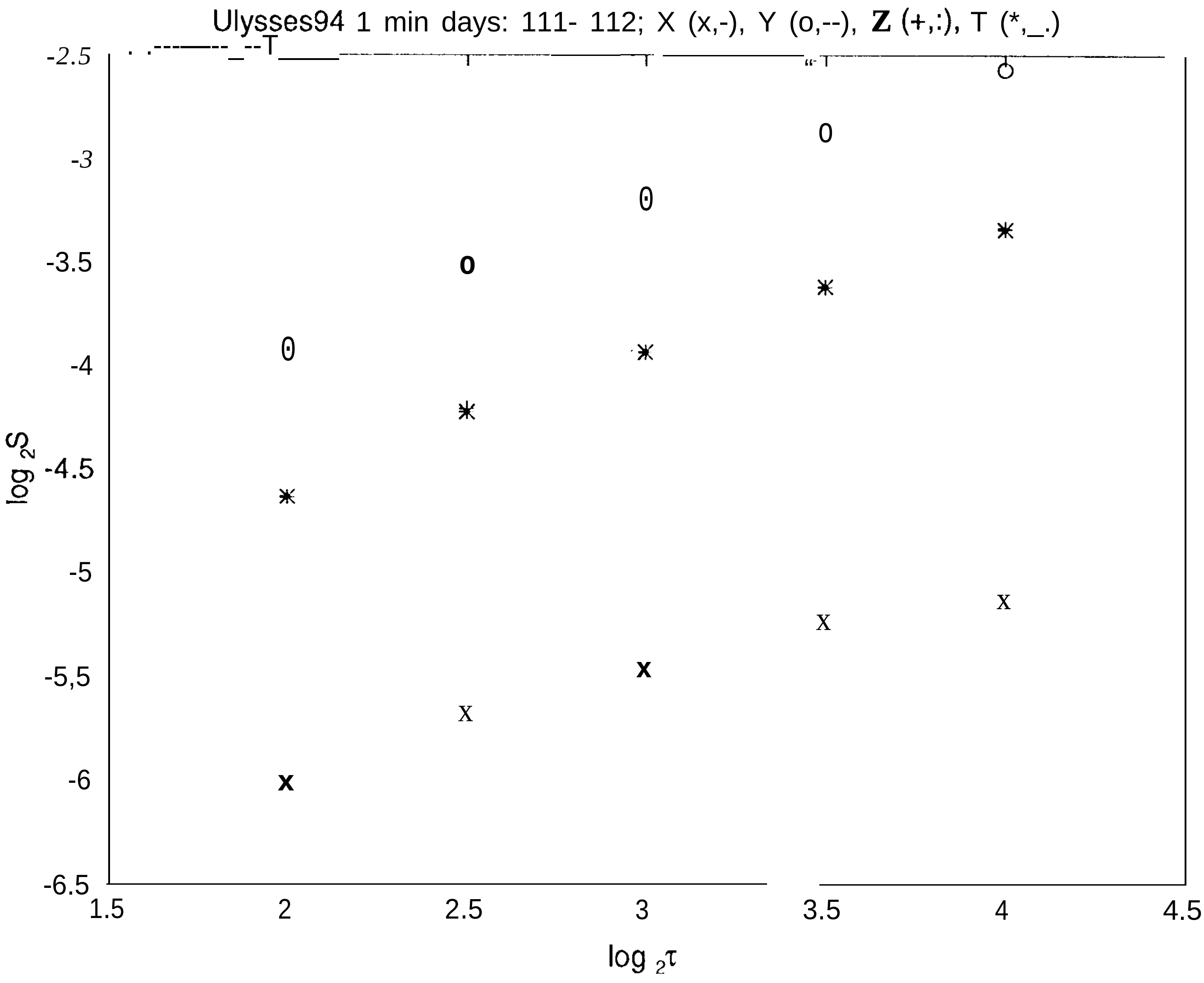


Ulysses94 1 min days: 318- 320; X (x), Y (0), Z (+)
C
τ
0.9
0.8
0.7
5
10
15
20
25
30
35



Ulysses94 1 min days: 111-112
Bx
By
Bz
B
t
0
200
400
600
800
1000
1200
1400
1600
1
0
-1
1.5
1
0.5


Ulysses94 lmin days: 111- 112; X (x), Y (o), Z (+)
C
τ
0
5
10
15
20
25
30
35
40
-0.2
0
0.2
0.4
0.6
0.8
1


Ulysses94 1 min days: 111- 112; X (x,-), Y (o,--), Z (+,:), T (*,_.)
log 2S
log 2τ
-2.5
-3
-3.5
-4
-4.5
-5
-5,5
-6
-6.5
1.5
2
2.5
3
3.5
4
4.5